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Analysis of defect related optical transitions in biased AlGaN/GaN heterostructures

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ABSTRACT

The optical transitions in AlGaN/GaN heterostructures that are grown by metalorganic chemical vapor deposition (MOCVD) have been investigated in detail by using Hall and room temperature (RT) photoluminescence (PL) measurements. The Hall measurements show that there is two-dimensional electron gas (2DEG) conduction at the AlGaN/GaN heterointerface. PL measurements show that in addition to the characteristic near-band edge (BE) transition, there are blue (BL) and yellow luminescence (YL) bands, free-exciton transition (FE), and a neighboring emission band (NEB). To analyze these transitions in detail, the PL measurements were taken under bias where the applied electric field changed from 0 to 50 V/cm. Due to the applied electric field, band bending occurs and NEB separates into two different peaks as an ultraviolet luminescence (UVL) and Y_4 band. Among these bands, only the yellow band is unaffected with the applied electric field. The luminescence intensity change of these bands with an electric field is investigated in detail. As a result, the most probable candidate of the intensity decrease with an increasing electric field is the reduction in the radiative lifetime.

1. Introduction

Group-III-nitride semiconductors and their alloys were studied extensively and used for optoelectronic [1,2] and electrical applications [3,4]. Due to the respective advantages such as high breakdown voltage, electron peak velocity, and high electron density, AlGaN/GaN heterostructures are advantageous for high-frequency and high-power applications at higher temperatures when compared with Si- and GaAs-based devices [5,6].

Because of the insufficient high quality lattice-matched substrates, AlGaN/GaN heterostructures are mostly grown on sapphire substrate, which causes a high number of dislocations. Dislocation related structural defects and other point defects (native defect, impurities, and complexes) notably affect the optical and electrical properties of the material [7]. Degradation of the performance and reliability of the group-III nitride semiconductor devices, originating from point defects, has been reported by many authors [8,9]. An in-depth understanding of point defects will lead to further improvements in device performance and reliability. Photoluminescence (PL) is one of the advanced defect detection and identification methods for semiconductors and has been extensively used for wide band-gap semiconductors when the electrical characterization is limited because of large activation energies beyond the thermal activation limits [10]. Recently, the luminescence properties of defects in GaN-systems have been reviewed extensively by Reschikov and Morkoç [10]. To investigate defect

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related electronic and optical properties in detail, one of the promising optical characterization methods is taking the PL measurements under bias [11,12].

In the present work, we investigated the electrical and optical properties of AlGaN/GaN heterostructures by using Hall and room temperature PL measurements. Defect related optical transitions were investigated by using RT PL measurements under bias where the applied electric field changed from 0 to 50 V/cm.

2. Experimental details

The investigated samples were grown on *c*-plane (0 0 0 1) sapphire (Al_2O_3) substrate in a low pressure MOCVD reactor. Before the epilayer growth, the sapphire substrate was cleaned in H_2 ambient at 1100 °C, and then a 25 nm-thick low temperature (LT) GaN nucleation layer was grown at 500 °C. The reactor pressure was set to 50 mbar during the substrate cleaning and nucleation growth. After the deposition of the LT-GaN nucleation layer, the wafer was heated to a high-temperature (HT) for annealing. The two-step growth process parameters of the ramp time and annealing temperature were 5 min and 1050 °C, respectively. Approximately a 2.5 μm thick GaN layer was deposited on the annealed nucleation layers by using constant growth conditions. Finally, a 25 nm thick $Al_{0.25}Ga_{0.75}N$ with a 3 nm GaN cap layer was grown. The layer structure of the samples is shown in Fig. 1 inset.

Hall Effect measurements were performed by using the van der Pauw (vdP) method. For the electrical measurements, the square shaped ($5 \times 5\,mm^2$) samples were prepared with Ti/Al/Ni/Au evaporated dot contacts in the corners. The ohmic behavior of the contacts was confirmed by the current voltage (*I–V*) characteristics. The measurements were performed at a 0.5 T magnetic field (with 0.1% uniformity) in a temperature range 20–350 K by using a Lakeshore Hall Effect Measurement System (HMS). At each temperature step, the Hall coefficient (with a maximum 5% error) and resistivity (with a maximum 0.2% error in the studied range) were measured and then the Hall mobility and Hall sheet carrier density values were calculated. The PL measurements were carried out at room temperature under a variable electric field (0–50 V/cm), which was applied to the opposite corners of the vdP sample. PL measurements were taken from the center of the sample where the maximum electric field intensity existed. For the PL measurements, the Horiba Jobin Yvon Fluorolog 3 spectrofluorometer with 325 nm ultraviolet light emitted from a 50 mW He–Cd laser excitation source was used.

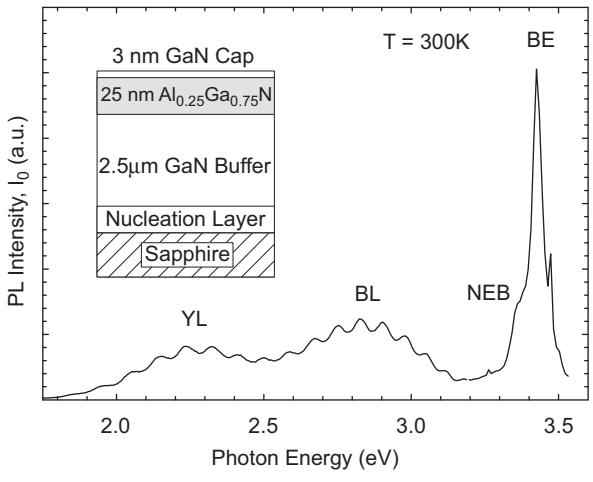

Fig. 1. PL spectrum of the AlGaN/GaN heterostructure at 300 K. Inset: layer structure of the investigated samples.

3. Results and discussion

The room temperature PL spectrum of the AlGaN/GaN heterostructure is shown in Fig. 1. The spectrum shows three main transitions, namely near-band edge (BE) transition, one broad blue luminescence (BL) band, and another broad yellow luminescence (YL) band centered at 3.42, 2.83, and 2.27 eV, respectively. There are fringes on the YL and BL bands, due to the multiple reflection of the laser light between the epilayers. In addition to these main transitions, neighboring emission band (NEB) that appears as a shoulder on the BE peak and free-exciton transition (FE) at 3.47 eV can be clearly seen in the figure.

The transition energies depend on the point defects such as the impurities that generally originate from unintentional doping and native defects. Generally, Si and C on the Ga sites (Si_{Ga} and C_{Ga}) and O on the N sites (O_N) are considered as shallow donors and Zn, Be, and Mg on the Ga sites (Zn_{Ga}, Be_{Ga}, Mg_{Ga}) and Si and C on the N sites (Si_N, C_N) are considered as shallow acceptors in GaN [10]. Due to the low formation energies of Si_{Ga} and O_N, these are the most probable impurity types in GaN. Native defects such as vacancies are related to non-stoichiometric growth or intentional doping, and significantly affect the optical properties of the material. In the *n*-type GaN, a gallium vacancy (V_{Ga}) is the dominant native defect, while the nitrogen vacancy (V_N) is the same as that in *p*-type GaN. It is well known that undoped GaN usually has *n*-type conductivity and gallium vacancy acts as an acceptor-like native defect which is responsible for this conductivity [13].

The BE transition is related to shallow donor bound exciton (DBE) and generally shows a sharp peak close to the energy gap of the semiconductor [14]. The dominant mechanism for BE luminescence is the formation of shallow donor due to V_N [15] and O_N [16].

Another emission band, called BL, which is centered at 2.83 eV in our case, sometimes appears in unintentionally doped GaN films at room temperature [17–19] and is related to the crystalline quality. The formation of a BL band is due to the recombination of the free electron in a conduction band (around room temperature) to relatively deep acceptor (e-A luminescence) levels. The observation of BL is typical for MOCVD grown GaN layers [18] and is related to some impurities coming from an MO source (Mg, Zn). The BL is dominated by the involvement of oxygen, carbon, and hydrogenated gallium vacancies in *n*-type GaN [20] and is associated with some metastable defects [21]. In our previous work, the presence of high concentrations of carbon and oxygen impurities in similar structures were shown by using the SIMS technique [22].

Besides for other emission bands, the most important one is the YL band that is centered at 2.27 eV, which occurs in nearly all GaN samples. Its position and shape are somewhat sample dependent [10] and strongly limit the optical applications of these materials [23]. The formation of this band is related to the transition of electrons from the conduction band to the deep acceptor states. These states are the evidence of native defects and residual impurities (compensating centers) [23–25] due to system contamination and background carrier concentration related to high-temperature GaN growth conditions. YL is not related to the specific impurity, wherein the most probable candidate is the deep acceptor (C_N) assisted gallium vacancy ($V_{Ga}C_N$) [10,26], in which it is believed that the presence of higher carbon impurity concentration in highly resistive films is an evidence of the reduced growth temperatures [27]. Even though the main mechanism behind the YL formation is unknown, there is much evidence that the YL originates from the GaN/sapphire interface.